

# MODELING AND INTELLIGENT CONTROL OF DOUBLE-LINK FLEXIBLE ROBOTIC MANIPULATOR

ANNISA BINTI JAMALI

A thesis submitted in fulfilment of the  
requirements for the award of the degree of  
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering  
Universiti Teknologi Malaysia

MARCH 2018

*In the name of ALLAH, The Most Gracious The Most Merciful*

*To my parents,*

*For raising me to believe everything is possible, taught me to trust in Allah, believe in hard  
work and that so much could be done with little.*

*To my husband, my girls and parents in law,*

*For endless support and making everything possible.*

*And to my supervisors,*

*For being my guardian during my Ph.D. journey.*

## ACKNOWLEDGEMENT

Thank You to The Almighty, The All-Knowing, The Wise *ALLAH* for giving me strength and ability to understand, learn and complete my research.

My deep gratitude goes first to my supervisor, Assoc. Prof Dr Intan Zaurah Mat Darus and Prof. M. Osman Tokhi who expertly guided me through my graduate education and who share the excitement of three years discovery. Their unwavering enthusiasm in the Vibration and Control System subject kept me constantly engaged with my research. And their personal generosity help make my graduate study enjoyable.

My appreciation extends to my laboratory colleagues; Sukri, Rickey, Fairus, Hanim, Ali, Jawad, Hussin and Hafizal. I am thankful to have a very supportive lab mates who continuously share and give ideas and keenly involve in discussing problems/challenges and issues rise during the study.

Above ground, I am indebted to my family: my parents, Jamali Seruji and Kusnudi Abu Bakar, my parents in law, Hazmi Abdullah and Mariam Zain, my siblings whose value to me only grows with age. And finally, I acknowledge my husband, Helmy Hazmi and my girls, Elzahraa and Elwafaa who bless me with the life of joys every single moment.

## ABSTRACT

The use of robotic manipulator with multi-link structure has a great influence in most of the current industries. However, controlling the motion of multi-link manipulator has become a challenging task especially when the flexible structure is used. Currently, the system utilizes the complex mathematics to solve desired hub angle with the coupling effect and vibration in the system. Thus, this research aims to develop a dynamic system and controller for double-link flexible robotics manipulator (DLFRM) with the improvement on hub angle position and vibration suppression. A laboratory sized DLFRM moving in horizontal direction is developed and fabricated to represent the actual dynamics of the system. The research utilized neural network as the model estimation. Results indicated that the identification of the DLFRM system using multi-layer perceptron (MLP) outperformed the Elman neural network (ENN). In the controllers' development, this research focuses on two main parts namely fixed controller and adaptive controller. In fixed controller, the metaheuristic algorithms known as Particle Swarm Optimization (PSO) and Artificial Bees Colony (ABC) were utilized to find optimum value of PID controller parameter to track the desired hub angle and suppress the vibration based on the identified models obtained earlier. For the adaptive controller, self-tuning using iterative learning algorithm (ILA) was implemented to adapt the controller parameters to meet the desired performances when there were changes to the system. It was observed that self-tuning using ILA can track the desired hub angle and suppress the vibration even when payload was added to the end effector of the system. In contrast, the fixed controller degraded when added payload exceeds 20 g. The performance of these control schemes was analysed separately via real-time PC-based control. The behaviour of the system response was observed in terms of trajectory tracking and vibration suppression. As a conclusion, it was found that the percentage of improvement achieved experimentally by the self-tuning controller over the fixed controller (PID-PSO) for settling time are 3.3 % and 3.28 % of each link respectively. The steady state errors of links 1 and 2 are improved by 91.9 % and 66.7 % respectively. Meanwhile, the vibration suppression for links 1 and 2 are improved by 76.7 % and 67.8 % respectively.

## ABSTRAK

Penggunaan pengolahan robotik dengan struktur pelbagai-pautan mempunyai pengaruh besar dalam kebanyakan industri semasa. Walau bagaimanapun, mengawal gerakan pengolahan pelbagai-pautan telah menjadi tugas yang mencabar terutama apabila struktur mudah lentur digunakan. Pada masa ini, sistem menggunakan matematik yang kompleks untuk menyelesaikan sudut hub yang dikehendaki dengan kesan gandingan dan getaran dalam sistem. Oleh itu, tujuan penyelidikan ini adalah untuk membentangkan satu sistem dinamik dan kawalan untuk pengolahan robotik mudah lentur (DLFRM) dengan penambahbaikan kedudukan sudut hub dan pengurangan getaran. DLFRM bersaiz makmal yang bergerak dalam arah mendatar dibangunkan dan dihasilkan untuk mewakili dinamik sebenar sistem. Penyelidikan ini menggunakan rangkaian saraf sebagai anggaran model. Keputusan menunjukkan bahawa pengenalan sistem DLFRM menggunakan *perceptron* pelbagai lapisan (MLP) mengatasi prestasi rangkaian neural Elman (ENN). Dalam pembangunan pengawal, penyelidikan ini memberi tumpuan kepada dua bahagian utama iaitu pengawal tetap dan pengawal suai. Dalam pengawal tetap, algoritma metaheuristik yang dikenali sebagai Pengoptimuman Kerumunan Zarah (PSO) dan Koloni Lebah Buatan (ABC) telah digunakan untuk mendapatkan nilai optimum bagi parameter pengawal PID untuk mengesan sudut hub yang dikehendaki dan mengurangkan getaran berdasarkan model yang dikenal pasti yang diperolehi sebelum ini. Untuk pengawal suai, penalaan diri menggunakan algoritma pembelajaran berlelaran (ILA) dilaksanakan bagi menyesuaikan parameter pengawal untuk memenuhi prestasi yang diinginkan apabila terdapat perubahan pada sistem. Daripada pemerhatian, didapati penalaan diri menggunakan ILA dapat menjejaki sudut yang dikehendaki dan getaran dikurangkan walaupun ketika muatan telah ditambahkan ke hujung pautan system. Sebaliknya, penalaan tetap merosot apabila muatan ditambah melebihi 20 g. Prestasi skema kawalan ini dianalisis secara berasingan berasaskan waktu sebenar melalui kawalan komputer. Tingkah laku tindak balas sistem diperhatikan dari segi pengesanan trajektori dan pengurangan getaran. Kesimpulannya, hasil kajian menunjukkan peratus penambahbaikan secara eksperimen yang dicapai dengan kawalan penalaan diri berbanding kawalan secara tetap (PID-PSO) untuk masa penyelesaian 3.3 % dan 3.28 % bagi setiap pautan masing-masing. Ralat keadaan mantap pautan 1 dan 2 dapat diperbaiki sebanyak masing-masing 91.9 % dan 66.7 %. Sementara itu, pengurangan getaran untuk pautan 1 dan 2 diperbaiki masing-masing sebanyak 76.7 % dan 67.8 %.

## TABLE OF CONTENT

CHAPTER	TITLE	PAGE
	<b>DECLARATION</b>	ii
	<b>DEDICATION</b>	iii
	<b>ACKNOWLEDGEMENTS</b>	iv
	<b>ABSTRACT</b>	v
	<b>ABSTRAK</b>	vi
	<b>TABLE OF CONTENT</b>	vii
	<b>LIST OF TABLES</b>	xii
	<b>LIST OF FIGURES</b>	xv
	<b>LIST OF ABBREVIATIONS</b>	xxiii
	<b>LIST OF SYMBOLS</b>	xxvi
	<b>LIST OF APPENDICES</b>	xxix
<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
	1.1 Background of the Problem	1
	1.2 Statement of the Problem	3
	1.3 Objectives of the Study	4
	1.4 Scope of the Study	5
	1.5 Significant Contribution to Knowledge	6
	1.6 Research Methodology	8
	1.7 Structure of Research	11
<b>2</b>	<b>LITERATURE REVIEW</b>	<b>14</b>
	2.1 Introduction	14
	2.2 Application of Flexible Robotic Manipulator	14
	2.3 Modeling and System Identification	16

	2.4 Control Strategy for MIMO System for Flexible Robotic Manipulator	20
	2.4.1 Decentralize Control Scheme	20
	2.4.2 Optimization Method	25
	2.5 PID Controller Tuned by Evolutionary Algorithm	27
	2.6 Self-Tuning Controller	31
	2.7 Research Gap	35
<b>3</b>	<b>SYSTEM RIG DESIGN AND EXPERIMENTAL SET UP</b>	<b>37</b>
	3.1 Introduction	37
	3.2 Development and Fabrication of Experimental Rig	37
	3.3 Instrumentation and Data Acquisition	39
	3.4 Actuator	40
	3.4.1 DC Motor	41
	3.4.1.1 Motor Controller	42
	3.4.1.2 Encoder	43
	3.4.2 Piezoelectric Actuator	45
	3.4.2.1 Piezo Amplifier	46
	3.5 Accelerometer	47
	3.6 System Integration	48
	3.7 Verification of Experimental Setup	50
	3.7.1 Experimental Test	50
	3.7.2 Impact Test	54
	3.7.3 Comparison between Experimental and Impact Test	58
	3.8 Summary	59
<b>4</b>	<b>NON-PARAMETRIC MODELING OF DOUBLE- LINK FLEXIBLE ROBOTIC MANIPULATOR</b>	<b>60</b>
	4.1 Introduction	60
	4.2 Data Acquisition	61
	4.3 Model Structure Formulation	64

4.4 Model Estimation: Non-Parametric Modeling	65
4.4.1 Multi-Layered Perceptron Neural Network	65
4.4.2 Elman Neural Network	67
4.4.3 Estimation of NARX Model using Neural Network Structure	70
4.5 Model Validation	71
4.5.1 One Step Ahead (OSA)	72
4.5.2 Mean Squared Error (MSE)	72
4.5.3 Correlation Test	73
4.6 Results and Discussion on System Identification	74
4.6.1 Modeling of Hub Angle	75
4.6.1.1 Multi-Layered Perceptron	75
4.6.1.2 Elman Neural Network	81
4.6.2 Modeling of End-Point Acceleration	87
4.6.2.1 Multi-Layered Perceptron	88
4.6.2.2 Elman Neural Network	93
4.6.3 Comparison	99
4.7 Summary	100
 <b>5</b>	
<b>CONTROLLER DEVELOPMENT OF DOUBLE- LINK FLEXIBLE ROBOTIC MANIPULATOR USING METAHEURISTIC ALGORITHMS</b>	<b>102</b>
5.1 Introduction	102
5.2 Control Scheme	104
5.3 PID-based Controller	106
5.3.1 Implementation of Rigid Body Motion	107
5.3.2 Implementation on Flexible Motion Control	108
5.4 PID controller tuned by Ziegler Nicholas	109
5.4.1 Rigid Body Motion	110
5.4.1.1 Simulation Results on Hub Angles 1 and 2	111



5.4.2 Flexible Body Motion	114
5.4.2.1 Simulation Results end-point acceleration 1 and 2	114
5.5 Intelligent PID Controller	117
5.5.1 Particle Swarm Optimization Algorithm	117
5.5.2 Artificial Bees Colony Algorithm	119
5.5.3 PID controller tuned by metaheuristic algorithm	121
5.5.4 Implementation of offline tuning of PID controller using PSO and ABC	123
5.4.1.1 PID tuned by PSO	125
5.4.2.1 PID Tuned by ABC	126
5.5.5 Simulation Result of Intelligent PID Controller	127
5.5.5.1 Hub Angle	128
5.5.5.2 End-Point Acceleration	130
5.6 Experimental validation of evolutionary algorithm based controller	133
5.6.1 Experimental Results	134
5.7 Robustness Test	138
5.7.1 Position of Actuator	138
5.7.2 Hub Angle Variation	143
5.7.3 Added mass payload	147
5.8 Summary	153

<b>6</b>	<b>REAL-TIME ITERATIVE LEARNING ALGORITHM FOR CONTROLLER'S IMPLEMENTATION</b>	<b>155</b>
6.1 Introduction		155
6.2 Self-Tuning PID-ILA Controller		156
6.2.1 Simulation Study on Self Tuning PID-ILA		159
6.2.1.1 Hub Angle		162
6.2.1.2 End-Point Acceleration		165

6.3 Experimental Validation of Self-Tuning PID-ILA	
Control Scheme	170
Experimental Results	173
6.4 Robustness Test	180
6.4.1 PID-ILA Controller using Step Input	181
6.4.2 PID-ILA Controller using bang-bang Input	188
6.5 Case Study: DLFRM coordination and Configuration	193
6.6 Discussion	197
6.7 Summary	198
<b>7 CONCLUSION AND FUTURE WORKS</b>	<b>199</b>
7.1 Conclusion	199
7.2 Future Works	202
<b>REFERENCES</b>	<b>204</b>
Appendices A-O	215-231

## LIST OF TABLES

<b>TABLE NO</b>	<b>TITLE</b>	<b>PAGE</b>
2.1	System identification of flexible manipulators	19
2.2	Decentralized controller for flexible manipulator	24
2.3	Controller scheme optimize by evolutionary algorithm for flexible manipulator system	26
2.4	PID tuned by evolutionary algorithm in flexible manipulator system	28
2.5	PID tuned by Evolutionary Algorithm in other Applications	30
2.6	Self-tuned controller in FLM system	32
2.7	Control scheme based on ILA in flexible link manipulator system.	33
3.1	Parameters of the DLFRM system	39
3.2	Specification of Motor 1 and Motor 2	41
3.3	Specification of Escon 50/5	42
3.4	Specification of Encoder 1 and Encoder 2	44
3.5	Specification of the piezoelectric actuator	45
3.6	Specification of the power amplifier	46
3.7	Specification of piezo beam accelerometer	47
3.8	Summary of the calculated and experimental frequency for link 1	58
3.9	Summary of the calculated and experimental frequency for link 2	58
4.1	MLP setting structure	67
4.2	ENN setting structure	69

4.3	Performance of MLP-NN for hub angle with different number of delay signals	75
4.4	Performance of MLP-NN for hub angle with different model structure	76
4.5	Performance of ENN for hub angle with numerous delay signals	81
4.6	Performance of ENN for hub angle with numerous model structures	82
4.7	Performance of MLP-NN for end-point acceleration with different number of delay signals	87
4.8	Performance of MLP-NN for end-point acceleration with different model structure	88
4.9	ENN results for end-point acceleration with numerous delays signals	93
4.10	ENN results for end-point acceleration with different model structure	94
4.11	Summary of the best performance achieved non-parametric modeling	99
5.1	Method 1 ZN-PID parameters	109
5.2	Comparison performance of Ziegler-Nichols method for hub angle 1	110
5.3	Comparison performance of Ziegler- Nichols method for hub angle 2	111
5.4	Method 2 ZN-PID parameters	113
5.5	Comparison performance of Z-N method for end-point acceleration 1	114
5.6	Comparison performance of Z-N method for end-point acceleration 1	115
5.7	Performance of PID-PSO, PID-ABC and PID-ZN controllers for hub angle 1.	127
5.8	Performance of PID-PSO, PID-ABC and PID-ZN controllers for hub angle 2	128

5.9	Performance of PID-PSO, PID-ABC and PID-ZN controllers for vibration suppression of link 1	130
5.10	Performance of PID-PSO, PID-ABC and PID-ZN controllers for vibration suppression of link 2	131
5.11	Performance of PID-PSO controllers for hub angle of DLFRM system.	135
5.12	Performance of PID-PSO controllers for vibration suppression of DLFRM system	137
5.13	Magnitude of vibration at the desired position	140
5.14	Controller performance of Vibration attenuation at different PZT position	142
5.15	Performance of PID-PSO controllers for hub angle of DLFRM system.	144
5.16	Attenuation level of the first mode at the end-effector of DLFRM.	151
6.1	Performance of controllers for hub angle	163
6.2	Performance of controllers for end-point acceleration	166
6.3	PID-ILA Performance for hub angle of DLFRM system.	173
6.4	Performance of PID-ILA controllers for vibration suppression of DLFRM system.	176
6.5	Performance of PID-ILA for hub angle of DLFRM system with various payloads.	181
6.6	Attenuation level of the first mode at the end-effector of DLFRM.	182
6.7	Performance of PID-PSO controllers for hub angle of DLFRM system	188

## LIST OF FIGURES

<b>FIGURE NO</b>	<b>TITLE</b>	<b>PAGE</b>
1.1	Flowchart of Research	9
3.1	Double-link flexible robotic manipulator	38
3.2	Connector shaft coupling of links 1 and 2	39
3.3	Data acquisition card PCI-6259	40
3.4	Connector block SCC-68	40
3.5	Motor	42
3.6	Escon 50/5	42
3.7	The orientation of quadrature encoder	44
3.8	Encoder HEDL 5540	44
3.9	Details sketch of DuraAct piezoelectric patch	45
3.10	Piezoelectric actuator amplifier type E-835 OEM	46
3.11	Piezo beam accelerometer type 8640A50	48
3.12	Schematic diagram of experimental set up	48
3.13	Experimental set up of double-link flexible robotic manipulator	49
3.14	Step input link 1	50
3.15	Step input link 2	51
3.16	Hub angle 1	52
3.17	Hub angle 2	52
3.18	End-point acceleration of link 1 in time and frequency domain	53
3.19	End-point acceleration for link 2 in time and frequency domain	54
3.20	MATLAB/Simulink for data collection of link	55
3.21	Impact test in time and frequency domain for link 1	56

3.22	Impact test in time and frequency domain for link 2	57
4.1	MATLAB/Simulink for data collection of DLFRM	62
4.2	Bang-bang input voltage	63
4.3	Experimental output response	63
4.4	MLP-NN algorithm diagram	65
4.5	Feed-forward dynamic neural network architecture.	66
4.6	Structure of MLP-NN	66
4.7	ENN algorithm diagram	68
4.8	A dynamic neural architecture with feedback	68
4.9	Structure of the ENN model	69
4.10	NNARX model structure	71
4.11	Learning curves- MSE against number of epochs of hub angle 1 model using MLP	78
4.12	Learning curves- MSE against number of epochs of hub angle 2 using MLP	78
4.13	Performance of Hub angle 1 model using MLP	79
4.14	Performance of Hub angle 2 model using MLP	79
4.15	Correlation test for hub angle 1 model using MLP	80
4.16	Correlation test for hub angle 2 model using MLP	81
4.17	Learning curves- MSE against number of epochs of hub angle 1 model using ENN	84
4.18	Learning curves- MSE against number of epochs of hub angle 2 model using ENN	84
4.19	Performance of hub angle 1 model using ENN	85
4.20	Performance of hub angle 2 model using ENN	85
4.21	Correlation test for hub angle 1 model using ENN	86
4.22	Correlation test for hub angle 2 model using ENN	87
4.23	Learning curves: MSE against number of epochs of link 1 for end-point acceleration model using MLP	90
4.24	Learning curves: MSE against number of epochs of link 2 for end-point acceleration model using MLP	90
4.25	Performance of end-point acceleration 1 model using	91

	MLP	
4.26	Performance of end-point acceleration 2 model using MLP	91
4.27	Correlation test for end-point acceleration 1 model using MLP	92
4.28	Correlation test for end-point acceleration 2 model using MLP	93
4.29	Learning curves: MSE against number of epochs of link 1 for end- point acceleration model using ENN	96
4.30	Learning curves: MSE against number of epochs of link 2 for end- point acceleration model using ENN	96
4.31	End-point acceleration 1 model using ENN	97
4.32	End-point acceleration 2 model using ENN	97
4.33	Correlation test for end-point acceleration 1 model using ENN	98
4.34	Correlation test for end-point acceleration 2 model using ENN	99
5.1	Block diagram of control schemes	106
5.2	Block diagram of each link for control rigid body motion	107
5.3	Block diagram of each link for control flexible body motion	109
5.4	Reference graph of method 1 Ziegler Nichols	110
5.5	Simulink model for hub angle	111
5.6	Results of hub angle 1	112
5.7	Results of hub angle 2	113
5.8	Reference graph of method 2 Ziegler Nichols	114
5.9	Simulink model for end-point acceleration	115
5.10	End-point vibration reduction of link 1	115
5.11	End-point vibration reduction of link 2	116
5.12	Flow chart of particle swarm optimization algorithm	118
5.13	Flowchart of artificial bees colony Algorithm	121



5.14	Block Diagram of the proposed PID control structure for hub angles 1 and 2.	122
5.15	Block Diagram of the proposed PID control structure for end-point accelerations 1 and 2	122
5.16	Flowchart of the simulation to tuned PID parameters	123
5.17	Simulink model for hub angle tuning by PSO and ABC	124
5.18	Simulink model for end-point acceleration tuning by PSO and ABC	124
5.19	PSO convergence hub angle	125
5.20	PSO convergence for end-point acceleration	126
5.21	ABC convergence for hub angle	127
5.22	ABC convergence for end-point acceleration	127
5.23	Tracking trajectory of hub angle 1 using ABC, PSO and ZN	128
5.24	Tracking trajectory of hub angle 2 using ABC, PSO and ZN	129
5.25	End-point vibration suppression of link 1 using ABC, PSO and ZN.	131
5.26	End-point vibration suppression of link 2 using ABC, PSO and ZN.	132
5.27	Simulink model for hub angle control of DLFRM using PID controller	133
5.28	Simulink model for end-point acceleration control of DLFRM using PID controller.	134
5.29	Experiment validation of racking trajectory of hub angle 1 using PSO	135
5.30	Experiment validation of racking trajectory of hub angle 2 using PSO	135
5.31	Experiment validation of end-point vibration suppression of link 1 using PSO	136
5.32	Experiment validation of end-point vibration suppression of link 2 using PSO	137
5.33	DLFRM in 7 segments	139

5.34	Vibration responses at the tip for different PZT actuator positions	140
5.35	Frequency responses at various PZT position of link 1	142
5.36	Frequency responses at various PZT position of link 2	142
5.37	Trajectory response of variation reference hub angle 1 using PSO	144
5.38	Trajectory response of variation reference hub angle 2 using PSO	145
5.39	Experiment validation of end-point vibration suppression using PSO	147
5.40	Frequency response at Section 3	147
5.41	Experiment validation of tracking trajectory of hub angle 1 using PSO	148
5.42	Experiment validation of tracking trajectory of hub angle 2 using PSO.	148
5.43	Vibration suppression with variation of payload	150
5.44	Frequency response of DLFRM under various payloads.	151
6.1	P-type ILA with PID controller	157
6.2	Block diagram of self-tuning control scheme based on ILA for hub angle 1 and 2	159
6.3	Block diagram of self-tuning control scheme based on ILA for end-point acceleration 1 and 2	160
6.4	Simulink model for hub angle based on ILA	161
6.5	Simulink model for end-point acceleration based on ILA.	161
6.6	Parameters convergence of hub angle 1 using PID-ILA controller.	162
6.7	Parameters convergence of hub angle 2 using PID-ILA controller.	163
6.8	Comparison between PID-ZN, PID-PSO and PID-ILA of hub angle 1	164
6.9	Comparison between PID-ZN, PID-PSO and PID-ILA of hub angle 2	164

6.10	Parameters convergence of end-point acceleration 1 using PID-ILA controller.	166
6.11	Parameters convergence of end-point acceleration 2 using PID-ILA controller.	166
6.12	Comparison between controllers for end-point acceleration 1	167
6.13	Comparison between controllers for end-point acceleration 2	167
6.14	Spectral density of the system output	169
6.15	GUI of real time system for hub angle control of DLFRM using PID-ILA controller	171
6.16	GUI of real time system for end-point acceleration control of DLFRM using PID-ILA controller.	172
6.17	Experiment validation of tracking trajectory of hub angle 1 using ILA	174
6.18	Experiment validation of tracking trajectory of hub angle 2 using ILA	174
6.19	Parameters convergence of hub angle 1 PID-ILA controller.	175
6.20	Parameters convergence of hub angle 2 PID-ILA controller.	175
6.21	Vibration suppression: Experiment validation using PID-ILA controller for end-point acceleration.	177
6.22	Parameters convergence of end-point acceleration 1 by using PID-ILA controller.	178
6.23	Parameters convergence of end-point acceleration 2 by using PID-ILA controller.	178
6.24	Spectral density of the output	179
6.25	The algorithm on PID parameter iteration for hub angle.	180
6.26	Experiment validation of tracking trajectory of hub angle 1 using ILA	181
6.27	Experiment validation of tracking trajectory of hub angle 2 using ILA	181

6.28	Parameters convergence of hub angle 1 using PID-ILA controller subjected to various payloads.	182
6.29	Parameters convergence of hub angle 2 using PID-ILA controller subjected to various payloads.	183
6.30	Frequency response of DLFRM under various payloads for link 1	186
6.31	Frequency response of DLFRM under various payloads for link 2.	187
6.32	Trajectory response of variation reference hub angle 1 using PID-ILA	188
6.33	Trajectory response of variation reference hub angle 2 using PID-ILA	189
6.34	Parameters convergence of hub angle 1 at various set points using PID-ILA controller.	190
6.35	Parameters convergence of hub angle 2 at various set points using PID-ILA controller.	190
6.36	Experiment validation of end-point vibration suppression of link 1 using ILA	192
6.37	Experiment validation of end-point vibration suppression of link 2 using ILA	192
6.38	Frequency response at Section 3	193
6.39	DLFRM configuration for elbow up and down	194
6.40	Tracking trajectory of hub angles 1 and 2	195
6.41	End point acceleration for links 1 and 2	195
6.42	DLFRM configuration for elbow up and down	196
6.43	Tracking trajectory of hub angles 1 and 2	196
6.44	End point acceleration for links 1 and 2	197

## LIST OF ABBREVIATIONS

ABC	-	Artificial bee colony
AMM	-	Assumed mode method
ARMAX	-	Auto-regressive Moving Average Models eXogenous inputs
ARX	-	Auto-regressive with exogenous input
ARX-BFA	-	Auto Regressive eXogenous inputs model with bacteria foraging algorithm
ARX-CS	-	Auto Regressive eXogenous inputs model with cuckoo search
ARX-DE	-	Auto Regressive eXogenous inputs model with differential evolutionary algorithm
ARX-PSO	-	Auto Regressive eXogenous inputs model with particle swarm optimization
AVC	-	Active vibration control
BFA	-	Bacteria foraging algorithm
BP	-	Back propagation
CS	-	Cuckoo search
DAQ	-	Data acquisition card
DC	-	Direct current
DCC	-	Decentralized control
DE	-	Differential evolution
DLFRM	-	Double-link flexible robotic manipulator
DOF	-	Degree of freedom
EA	-	Evolutionary algorithm
ENN	-	Elman neural network
FEM	-	Finite element method

FLC	-	Fuzzy logic controller
FLM	-	Flexible link manipulator
GA	-	Genetic Algorithm
GUI	-	Graphical user interface
ILA	-	Iterative learning algorithm
LM	-	Levenberg-Marquardt
LMI	-	Linear matrix inequalities
LS	-	Least square
MIMO	-	Multiple-input multiple-output
MLP	-	Multilayer Perceptron Neural Network
MLP-NN-BP	-	Multilayer perceptron neural network using back propagation
MODE	-	Multi-objective optimization using differential evolution
MOPSO	-	Multi-objective PSO
MPC	-	Model predictive control
MSE	-	Mean square error
NARMAX	-	Nonlinear Auto-regressive Moving Average Models eXogenous
NARMAX-RELS	-	Nonlinear Auto-regressive Moving Average Models eXogenous inputs with recursive extended least square
NARX	-	Nonlinear auto-regressive with exogenous input
NARX-LS	-	Auto Regressive eXogenous with least square
NI	-	National Instrumentation
NN	-	Neural network
NNARX	-	Neural network nonlinear Auto Regressive exogenous
OSA	-	One step ahead
PD	-	Proportional derivative
PID	-	Proportional integral derivative
PID-ZN	-	Proportional integral derivative Ziegler-Nichols
PID-PSO	-	Proportional integral derivative particle swarm optimization
PID-ABC	-	Proportional integral derivative artificial bee colony
PID-ILA	-	Proportional integral derivative iterative learning algorithm
PSO	-	Particle swarm optimization

PWM	-	Pulse width modulation
PZT	-	Piezoelectric
RGA	-	Relative gain array
RLS	-	Recursive least square
RELS		Recursive extended least square
SDA	-	Spiral dynamic algorithm
SI	-	System identification
SIMO	-	Single-input multiple-outputs
SISO	-	Single-input single-output system
SLFM	-	Single link flexible manipulator
SSE	-	Steady state error
STC	-	Self-tuning controller
SO	-	Single objective
TDL	-	Tapped delay lines
ZN	-	Ziegler-Nichols

## LIST OF SYMBOLS

$A_m$	-	Transfer function of motor gain for hub angle motion
$A_p$	-	Transfer function of actuator gain for flexible body motion
$C_m$	-	Transfer function of controller for hub angle motion
$C_p$	-	Transfer function of controller for flexible body motion
$C_1, C_2$	-	Learning factors
$d(X)$	-	Performance derivatives
$dX_{prev}$	-	Former adjustment to the weight or bias
$\delta(\tau)$	-	Impulse
$E$	-	Modulus of elasticity
$E_{ss}$	-	Steady state error
$e_p(t)$	-	Error of the system for flexible body motion
$e_m(t)$	-	Error of the system for hub angle motion
$e(k)$	-	System error
$\varepsilon$	-	Residual
$f(\cdot)$	-	Function
$f_{min}(e)$	-	Mean squared error
$fit_m$	-	Fitness of $x_m$
$G_p$	-	Transfer function of sensor for flexible body motion
$g_{best}$	-	Global best
$G_m$	-	Transfer function of sensor for hub angle motion
$\theta(t)$	-	Hub angle
$\theta_d(t)$	-	Desired hub angle
$\theta_i(t)$	-	Hub angle output
$i$	-	Number of link
$I_{cont}$	-	Output current
$j$	-	Number of neuron of MLP



$K_P$	-	proportional gain,
$K_I$	-	Integral gain
$K_D$	-	Derivative gain
$K_{cr}$	-	Critical value
$K(k)$	-	Stored value from the previous iteration (from memory)
$K(k+1)$	-	Updated value (to memory)
$L$	-	Delay time
$M_p$	-	Maximum overshoot
$N$	-	Number of data
$PID_{i1}$	-	PID controller hub angle motion for i link
$PID_{i2}$	-	PID controller flexible body motion for i link
$P_{cr}$	-	Period
$p_{best}$	-	Best solution PSO has achieved so far
$P_m$	-	Profitability of all food sources
$R_1, R_2$	-	Random number
$T$	-	Time constant
$t_r$	-	Rise time
$t_s$	-	Settling time
$\tau(t)$	-	Torque
$U_{mi}$	-	PID control output for hub angle of i link
$U_{pi}$	-	PID control output for flexible body motion of i link
$V_{cc}$	-	Operating voltage
$v_{mi}$	-	Neighbour food source
$V$	-	Particle velocity
$\phi$	-	Regression vector of NNARX
$\Phi_P$	-	Proportional learning parameter
$\Phi_I$	-	Integral learning parameter
$\Phi_D$	-	Derivative learning parameter
$W$	-	Inertia weight
$w_{ij}$	-	Weight of strength of MLP
$X$	-	Particle position
$x$	-	Bias
$x_m$	-	Initial food sources

$x_i$	-	Input layer of MLP
$y_d(t)$	-	Desired end-point acceleration
$y_i(t)$	-	End-point acceleration output
$y(t)$	-	End-point acceleration
$y_d(k)$	-	Desired input
$y(k)$	-	Actual output
$y_v(t)$	-	Disturbance to the system.
$\hat{y}$	-	Forecast/predict output
$y_j$	-	Output of MLP
$Z^N$	-	Training data set

## LIST OF APPENDICES

<b>APPENDIX</b>	<b>TITLE</b>	<b>PAGE</b>
A	List of Publication	208
B	Technical specification of DC Motor 1	209
C	Technical specification of encoder motor 1	210
D	Technical specification of motor gearhead	211
E	Technical specification of DC Motor 2	212
F	Technical specification of encoder motor 2	213
G	Technical specification of motor driver	214
H	Technical specification of data acquisition system (DAQ)	215
I	Technical specification of piezoelectric actuator	216
J	Technical specification of piezoelectric actuator amplifier	217
K	Technical specification of accelerometer	218
L	Technical specification of accelerometer input	219

## **CHAPTER 1**

### **INTRODUCTION**

#### **1.1 Background of Study**

Robotic manipulators are extensively used in industries and other fields at various level of operation that is from simple pick and place task to the critical operation such as space manipulator, automotive, security, electronic factory, medicine, oil and gas, etc. This is because they are cost effective and proven to be more reliable than humans. In term of design, robotic manipulator structures are generally substantial and heavy that result in rigid arm and stiff joint design. Their usages are limited to light loads and their movement is slow. Hence, the conventional design is not favorable in current industries as it is not efficient in term of speed, productivity and power consumption. Apart from that, many industries require light mechanical structure such as spacecraft and aircraft. Therefore, noteworthy attention has been given to flexible manipulator systems in recent years to fulfill the necessity of industrial applications. There are lots of benefits from the development of the flexible manipulator structure: cost reduction, lower power consumption, improved dexterity, better maneuverability, better transportability, safer operation, light weight and lower environmental impact.

Though flexible structure provides accommodating structure for design, it is known that the systems demonstrate vibration when subject to disturbances forces. The vibration occurs in the light weight manipulators cannot be avoided whenever

they maneuver from one point to another. The vibration can be very severe to the extent that results in noise, disturbances and discomfort. Vibration may cause performance degradation, tracking errors, long idle period between tasks, undermining accuracy and safety. In the worst-case, vibration may cause premature deterioration of the system. Therefore, it is vital to control the vibration of flexible structures.

Ongoing researches of flexible structure focused on improving the control methods to fulfill all conflicting between benefits, drawbacks and industries requirements. In suppressing the vibration, there are two different techniques that are hitherto utilised, namely passive control techniques and active control techniques. Though there is research on passive control in flexible manipulator (Feliu *et al.*, 2014; Emiliano *et al.*, 2007; Forbes and Damaren, 2012), but most of the researches concentrated on using active vibration technique. Active control uses the principle of wave interference by artificially generating a destructive anti source that interferes with the disturbances and reduces the level of vibration. In other word, a suitable control will process the detected vibration in the system, then superimpose disturbance signals to free the system from the actual disturbance force. Meanwhile, a passive control requires additional weight embedded to the system as an absorber which is simpler, but it is applied to the system with high frequency which is more than 200 Hz. Besides, engaging passive control may contradict with the objective to reduce the weight of mechanical structures. Furthermore, the flexible manipulator system is found to be categorized under low frequency system. Thus, in comparison, active control is found to be more suitable and practical to be applied to the system. It has been widely used by many researchers and is still the prominent approach till today.

To date, a number of control strategies are available for double-link flexible robotic manipulator (DLFRM) such as Passivity-based velocity feedback and strain-feedback schemes (Peza-Solís *et al.*, 2010), hybrid collocated proportional derivative (PD) and non-collocated proportional integral derivative (PID) (Mahamood and Pedro, 2011a), global terminal sliding mode (Chu *et al.* 2009), a genetic algorithm (GA) based hybrid fuzzy logic control strategy (Zebin and Alam, 2010), decoupling

controller based on the cloud model (Lingbo *et al.*, 2006), decentralized controller based on linear matrix inequalities (Khairudin and Husain, 2014; Leena and Ray, 2012). The strategies include both conventional and intelligent schemes. Some of them combine both intelligent and conventional scheme to compensate the drawback of each controller.

## 1.2 Statement of the Problem

The advancements in various field of life inclusive of domestic and industries create a great demand for flexible robot manipulator. Many robot manipulator applications are categorized as multiple-input-multiple-output (MIMO) systems due to multi-link structure. The design and tuning of multi-loop controllers to meet certain specifications are often the pullback factor because there are interactions between the controllers. The system must be decoupled first to minimize the interaction or to make the system diagonally dominant. Moreover, the reduction of vibration on flexible structure of robot manipulator must be treated at the same time. The continuous stress produced by the vibration can lead to structural deterioration, fatigue, instability and performance degradation. Thus, the reduction of vibration on flexible structure of robot manipulator is of paramount importance. Though many researchers have successfully produced the controllers for multi-link flexible manipulator, the control scheme developed involves complex mathematics to solve the coupling effect and vibration simultaneously. As a result, it consumes a lot of time in numerical computation which leads to higher computational cost.

In the attempt of providing a better control performance, the preferable option for control strategy that involves MIMO system is decentralized control strategy because it reduces the system into single-input single-output system (SISO). Simultaneous optimization method is an alternative of optimizing the parameters without go through the complex mathematical calculation to decouple the system. Meanwhile, AVC is opted to optimally reduce vibration. For implementing AVC in flexible manipulator, smart material is embedded to the system.

Thus, this thesis aims to manage the MIMO system along with the existence of vibration in them. In this research, the hybrid PID-PID controller is developed for hub motion and end point vibration suppression of each link respectively. The optimization procedure of PID control parameters are tackled using EA and ILA. Two EAs are implemented, namely, Particle Swarm Optimization (PSO) and Artificial Bees Colonial Algorithm (ABC). Meanwhile, for adaptive controller, self-tuning of P-Type ILA employed to the system. The PID control tuning method using EAs and ILA are implemented on the identified model through system identification acquisition of the real plant using neural network structure based on NARX model. The performance of EA and ILA is then analyzed via experimental validation. Self-tuning using iterative learning algorithm (ILA) was implemented to adapt the controller parameters to meet the desired performances when there were changes to the system.

### **1.3 Objectives of the Study**

This research focuses on the control strategies of the double-link flexible robotic manipulator. The objectives are as such;

1. To model the dynamic of double-link flexible robotic manipulator with actual experimental input-output data using non-parametric system identification (SI) utilizing Neural Network Non-linear Auto Regressive exogenous (NNARX) structure.
2. To develop conventional and intelligent hybrid PID controllers that can achieve desired angle of each link together with the suppression of the unwanted tip vibration on the double-link flexible robotic manipulator based on the identified model.

3. To develop, simulate and analyze the performance of real time self-tuning PID controller in controlling the angle and vibration of double-link flexible robotic manipulator.
4. To analyze, verify and validate the best intelligent hybrid PID and self-tuning PID controllers experimentally and to perform the comparative assessment between those controllers.

#### **1.4 Scope of the Study**

The scope of the research is as follows;

1. Development and fabrication of a laboratory scale size of double-link flexible robotic manipulator to move in horizontal planar direction only and gravity effect is neglected.
2. The non-parametric model approach is used to model the dynamic of double-link flexible robotic manipulator limited to multilayer perceptron neural network (MLP) and Elman neural network (ENN) based on Nonlinear autoregressive with exogenous input (NARX) structure. All the developed models are validated via mean square error (MSE), one step ahead (OSA) prediction and correlation tests only.
3. Rigid and flexible motion controls of DLFRM are conducted using two different control loops respectively based on decentralized control strategy only. The rigid motion is evaluated via the input tracking only and the performance of the flexible motion is assessed through vibration attenuation at the first mode of vibration.
4. The intelligent controls are designed and simulated by applying PID controller tuned via offline, limited to particle swarm optimization (PSO) and



artificial bee colony (ABC) and compared with conventional fixed Ziegler-Nichols (ZN) PID controller. The best control scheme of fixed controller obtained from the simulation is validated experimentally via the developed DLFRM rig.

5. The real time self-tuning PID control schemes limited to P-type iterative learning algorithm (ILA). The controller is implemented for input tracking and vibration suppression via the developed DLFRM experimental rig.
6. The robustness test for the PID control scheme on the experimental rig is limited to angle variation and end point payload.

## **1.5 Significant Contribution to Knowledge**

The contributions of the research are focused on four main areas that is in the development of model using experimental data from the rig, the development of controllers via decentralized control strategies, the implementation of simultaneous optimization method via evolutionary algorithm in solving the parameter of hybrid PID MIMO system and real time self-tuning PID based controllers. The details are elaborated herein;

1. This research contributes in developing the dynamic model of the double-link flexible robotic manipulator using non-parametric system identification approach. Most of the previous researches used model-based mathematical modeling such as assumed mode method (AMM), finite element method (FEM) and lump parameters and quite a number implement non-model based such as using neural network (NN), fuzzy and neuro-fuzzy. In this research, the model is developed using both input and output data from the experiment of double-link flexible robotic manipulator system based on NARX model structure model. Two types of parameter estimation were used for the model development that is multilayer perceptron neural network using back

propagation as training algorithm (MLP-NN-BP) and Elman neural network. The models were verified through mean squared error, one step ahead and correlation tests to determine the best model that represents the system. Thus, the controller was designed based on NNARX model which represent the nonlinear model of the system. Number of research in this area control the system via linear model of the system which is not preferable because it does not represent the real plant.

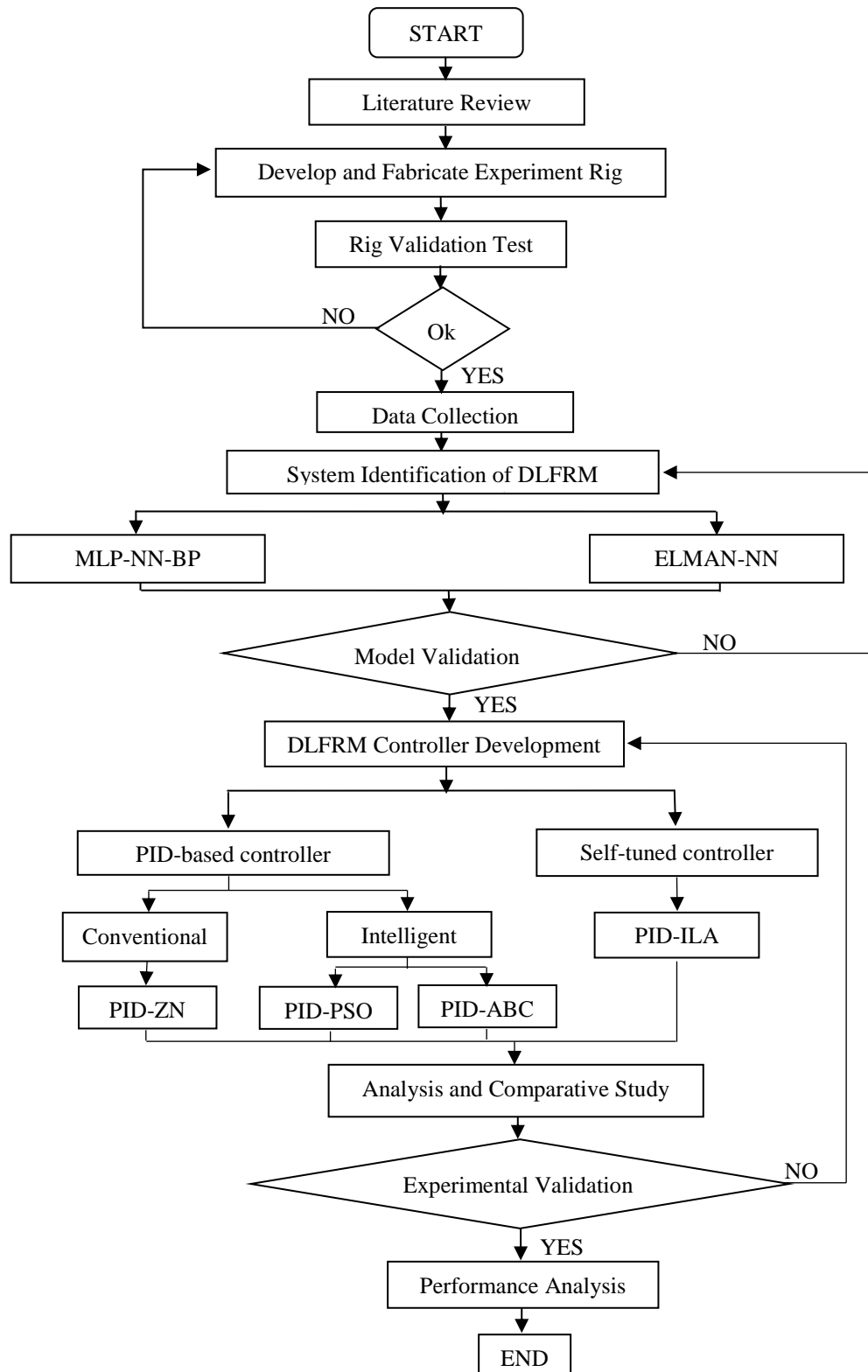
2. This research contributes in developing a new method using hybrid PID controller on DLFRM with decentralized control strategy via simultaneous optimization method. Problem arises as the systems consist of single-input multiple-outputs (SIMO) as a separate system and become MIMO system as the system merge. The simultaneous optimization method is implemented to the MIMO system. Despite the fact that many researches had implemented this method, most of them has pre-calculated the decouple gain and use the optimization method on decoupled matrix. Whereas, in this research, the optimization is implemented directly on the obtained models from system identification for all the PID controllers. Thus, the novelty of this research is that the dynamic models of DLFRM are separated in the modeling stage. By that, the characteristics of DLFRM are defined in each model and the coupling effect is assumed to be minimized. There is no study yet to implement this approach. Besides, the intelligent Hybrid PID controllers tuned by PSO and ABC have not been reported previously to control the rigid and flexible motion of DLFRM. Thus, in this study, the simultaneous optimization method using PSO and ABC are developed to observe the mathematical burden in calculating the decouple gain due to coupling effect.
3. This research contributes in investigating the implementation of controlling MIMO system using decentralized control strategies in the actual plant. The models are controlled within the simulation environment to pre-determine the appropriate gains for PID controllers before the experimental work is employed. Later, the performances of the simulated controllers are validated

experimentally. All the four controllers are run simultaneously on the real plant which has not been conducted previously.

4. The real time self-tuning iterative learning algorithm PID based controllers is simulated and validated experimentally. The system is controlled concurrently by all the four controllers in real time. Besides, the study provides details implementation of new control structure in controlling DLFRM under variation of payloads via online which has not been reported in any research. From the experiment, these controllers are proven to be robust in term of the input tracking and vibration suppression though there is a change of payloads at the end-effector. This is a great advantageous of the controllers and it is very important characteristics to be implemented in the real application.

## **1.6 Research Methodology**

The extensive literature review on the subject matter was carried out to properly decide the direction of the study. The research consists of several phases: system identification, controller design and experimental validation as shown in Figure 1.1. Before that, the experimental rig was developed and fabricated. The fabrication of the rig was aimed to replicate the dynamics of the actual systems. The instrumentation and data acquisition system were setup and integrated with the DLFRM rig.



**Figure 1.1** Flowchart of Research

The impact test was executed to the DLFRM system to validate the rig. The first three modes of vibration were identified from the findings. This is an important element in vibration control. The results were to be compared with the experimental studies. From there, the validity of the developed model could be confirmed.

Then the model of double-link flexible robotic manipulator was identified through SI. The input-output data required for the modeling process were collected experimentally using the DLFRM test rig. Simulink program was developed as the tool for collecting the data. Four outputs were collected from two encoders and two accelerometers which represent the hub angles and end point accelerations of each link respectively. Nonlinear auto-regressive with exogenous input model structure was used to define the relationship between input and output data. The model was estimated using neural network that is multi-layer perceptron and Elman neural network. The model was validated through MSE, OSA and correlation tests. The fittest model was selected as the platform or plant for the PID controller design in the simulation environment.

Once the model has been selected, the controllers were developed. Three types of controllers were designed that is conventional controller, intelligent PID controller and self-tuned controller. Conventional controller acts as the experiment control of the controller design. The algorithm was used to compute the amount of torque (motor voltage) required for trajectory tracking and the amount of voltage from actuator to suppress the vibration for DLFRM system. The PID control scheme was tuned offline by intelligent tuning methods using ABC and PSO. Meanwhile, the conventional tuning method implemented Ziegler-Nichols method. The performance of the intelligent fixed PID control schemes were compared with a conventional, fixed PID control scheme.

The best performances of fixed PID controllers obtained from the simulation evaluations were validated experimentally using the developed DLFRM rig. For self-tuning PID control scheme, the ILA was incorporated with the PID controller to update its parameters iteratively. P-Type ILA was used to tune the PID controller parameters for both trajectory tracking and end point acceleration control of

DLFRM. The real time self-tuning PID control scheme was executed through the developed experimental rig for trajectory tracking control and end point acceleration. Finally, a comparative study between fixed and self-tuning PID control schemes were conducted and reported. The objective of the comparative study was to observe the differences in their performance simultaneously. From there, the researchers can exploit the benefits of using the proposed strategies. Figure 1.1 shows the flow chart of the proposed research strategy considered in this study.

## 1.7 Structure of Research

This thesis is organized into seven chapters. A brief outline of contents of the thesis is as follows:

**Chapter 1** presents an introduction of the research problem. It comprises the research background and problem statement. Besides, the research objectives, contributions and methodology are highlighted and elaborated. The structure and the flow of the thesis are also outlined in this chapter.

**Chapter 2** focuses on the literature review of modeling and control for the flexible manipulators. Firstly, a brief overview on modeling approaches and control schemes of the flexible manipulators was highlighted. Then, the recent proposed model schemes were reviewed. This was followed by the review on the numerous proposed control schemes and their various applications. The gaps between the earlier researches and the proposed modeling and control schemes were recognized and discussed.

**Chapter 3** describes the development of experimental test rig to perform the planar movement of double-link flexible robotic manipulator. The rig design, the hardware use in the experiment set up and the system integration were elaborated in details. Besides, the method of data acquisitions was elucidated. The chapter also clarified

the reliability of the developed experimental rig through the experimental and impact test carried out on the system.

**Chapter 4** presents the implementation of SI in modeling the hub-angle and end point vibration of the DLFRM. The NARX model structure was selected to characterize the actual system. The MLP neural network and Elman neural network techniques were utilized to estimate and obtain the model of the system. This chapter starts with brief explanation of neural network and NARX model structure in general. Then, the details of model estimation were discussed which involved the incorporation of NARX model structure and neural network. The comparative study among the developed models in terms of MSE, OSA and correlation tests were carried out. The best model among the developed models was utilized as a system plant in the development of control via simulation environment.

**Chapter 5** presents new tuning methodologies of the conventional PID controller by using metaheuristic algorithms. The algorithm is expected to optimally track the desired hub-angle together with vibration suppression of the DLFRM. This chapter starts with simulation studies of three types of PID based controller configurations that implemented and tuned the controller based on Ziegler Nichols method. The performance of the hub angle control and end point acceleration of DLFRM are evaluated. The best among the controllers is to be compared with the proposed controllers. Next, the implementation of tuning the PID-based controller offline on the identified hub-angle model and end point acceleration to obtain the controllers parameters are discussed. The optimization process uses the metaheuristic algorithms that are ABC and PSO by targeting the position of the hub angle and vibration suppression. PID-based parameters are validated experimentally and the performance of PID-based controller tuned by ABC was compared with PSO. Lastly, the robustness tests were carried out to evaluate the effectiveness of the controller.

**Chapter 6** presents the development of real time self-tuning PID control scheme based on ILA for DLFRM. The proposed controllers were observed via simulation environment before executed on experimental rig. The self-tuning PID controller

performance was validated experimentally and compared with the fixed control schemes. The effectiveness of the controller was validated through robustness tests.

**Chapter 7** summarizes the work presented and draws significant conclusions. Suggestion on the possible future works for modeling and control of DLFRM are also discussed.



## REFERENCES

- Abdulhussain, A., Al-Khafaji, M., and Mat Darus, I.Z. (2013). Cuckoo Search for Modelling of a Flexible Single-Link Manipulator. *Manufacturing Engineering, Automatic Control and Robotics*.
- Abdullah M. Almeshal, M. R. A., and H.Alzanki, T. (2014). A Spiral Dynamic Optimised Hybrid Fuzzy Logic Controller for Unicycle Mobile Robot on Irregular Terrains. *World Academy of Science, Engineering and Technology*, 8(10), 1508–1512.
- Ahn, H-S., Chen, Y. and Moore, K. L. (2007). Iterative learning control: Brief survey and categorization. *IEEE Transactions on Systems, Man and Cybernetics Part C: Applications and Reviews*, 37(6):1099-1121.
- Alam, M. S., Md Zain, M. Z., Tokhi, M. O., and Aldebrez, F. (2005). Design of hybrid learning control for flexible manipulators: A multi-objective optimisation approach. *Proceedings of the 8th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines, CLAWAR 2005*, 599–606.
- Al-Mola, M., Mailah, M., Muhaimin, A. H., Abdullah, M. Y. and Samin, P. M. (2012). Fuzzy-based PID with iterative learning active force controller for an anti-lock brake system. *International Journal of Simulation: Systems, Science and Technology*, 13(3 A), 35–41
- Alavandar, S., Jain, T. and Nigam, M. J. (2009). Bacterial Foraging Optimized Hybrid Fuzzy Pre-compensated PD Control of Two Link Rigid-Flexible Manipulator. *International Journal of Computational Intelligence Systems*, 2(1), 51–59.
- Ali, H., Hariharan, M., Yaacob, S. and Adom, A.H. (2015). Facial emotion recognition using empirical mode decomposition. *Expert Systems with Applications*, 42(3), 1261–1277.

- Amador-angulo, L. and Castillo, O. (2014). Optimization of the Type-1 and Type-2 Fuzzy Controller design for the Water Tank using the Bee Colony Optimization. *In Norbert Wiener in the 21st Century*, 1–8.
- Anisi, D. A. and Skourup, C. (2012). A step-wise approach to oil and gas robotics. *In IFAC Workshop on Automatic Control in Offshore Oil and Gas Production*, 47–52.
- Annisa, J., R. Khan and M. M. Rahman (2011). A new geometrical approach to solve inverse kinematics of hyper redundant robots with variable link length. *2011 4th International Conference on Mechatronics (ICOM), Kuala Lumpur*, 1-5.
- Antić, D., Milovanović, M., Nikolić, S., Milojković, M. and Perić, S. (2013). Simulation Model of Magnetic Levitation Based on NARX Neural Networks. *International Journal Intelligent System and Applications*, (5), 25–32.
- Bai, M., Zhou, D. H., and Schwarz, H. (1998). Adaptive Augmented State Feedback Control for an Experimental Planar Two-Link Flexible Manipulator. *Transactions on Robotics and Automation*, 14(6), 940–950.
- Basso, M., Giarre, L., Groppi, S., and Zappa, G. (2005). NARX Models of an Industrial Power Plant Gas Turbine. *IEEE Transaction on Control Systems Technology*, 13(4), 599–604.
- Becedas, J., Trapero, J. R., Feliu, V., and Sira-Ramirez, H. (2009). Adaptive controller for single-link flexible manipulators based on algebraic identification and generalized proportional integral control. *IEEE Transactions on Systems, Man, and Cybernetics Society*, 39(3), 735–51.
- Billings, S. A. and Zhu, O. M. (1994). Non-Linear Model Validation Correlation Tests. *International Journal of Control*, 60(6), 1107–1120.
- Blevins, R. D. (1979). *Formulas for Natural Frequency & Mode Shape*. New York: Van Nostrand Reinhold.
- Boyd, S., Hast, M. and Aström, K. J. (2015). MIMO PID Tuning via Iterated LMI Restriction. *International Journal Robust Nonlinear Control*.
- Cetinkunt, S., Siciliano, B., and J. Book, W. (1987). Symbolic modeling and dynamic analysis of flexible manipulators. *Robotics and Automation*, 4, 2074–2080.
- Chang, T. K., Spowage, A., and Yoong, C. K. (2015). Review of Control and Sensor System of Flexible. *Journal International Robot System*, (77), 187–213.

- Chien, C. and Tayebi, A. (2008). Further results on adaptive iterative learning control of robot manipulators. *Automatica*, 44, 830–837.
- Chu, M., Jia, Q. X., and Sun, H. X. (2009). Global terminal sliding mode robust control for trajectory tracking and vibration suppression of two-link flexible space manipulator. *In Proceedings of 2009 IEEE International Conference on Intelligent Computing and Intelligent Systems*, 353–357.
- Dogan, M. and Istefanopulos, Y. (2007). Optimal nonlinear controller design for flexible robot manipulators with adaptive internal model. *IET Control Theory Application*, 1(3), 770–778.
- Dynapar (2017), Quadrature Encoder Overview. Retrieved on 3 Jan, 2017, from [http://www.dynapar.com/Technology/Encoder\\_Basics/Quadrature\\_Encoder/](http://www.dynapar.com/Technology/Encoder_Basics/Quadrature_Encoder/)
- Pereira, E.I., Diaz, M.J., Cela J. L. and Feliu V. (2007). A new design methodology for passivity-based control of single-link flexible manipulators. *2007 IEEE/ASME international conference on advanced intelligent mechatronics, Zurich*, 1-6.
- Fahmy, A. A., Kalyoncu, M., and Castellani, M. (2011). Automatic design of control systems for robot manipulators using the bees algorithm. *Journal of Systems and Control Engineering*, 1, 1–12.
- Fareh, R., Saad, M. and Saad, M. (2014). Distributed control strategy for flexible link manipulators. *Robotica*, 1–19.
- Farid, M. and Lukasiewicz, S. A. (2000). Dynamic modeling of spatial manipulators with flexible links and joints. *Computers and Structures*, 75, 419–437.
- Feliu, V., Pereira, E. and Díaz, I. M. (2014). Passivity-based control of single-link flexible manipulators using a linear strain feedback. *Mechanism and Machine Theory*, (71), 191–208.
- Feliu, V., Rattan, K. S., and Brown, H. B. (1990). Adaptive Control of a Single-Link Flexible Manipulator. *In 1989 IEEE International Conference on Robotics and Automation*, 29–33.
- Feliu, V., Rattan, K. S. and Brown, H. B. (1992). Modeling and Control of Single-Link Flexible Arms with Lumped Masses. *Journal of Dynamic Systems, Measurement, and Control*, 114(1), 59.
- Forbes, J. R. and Damaren, C. J. (2012). Single-Link Flexible Manipulator Control Accommodating Passivity Violations: Theory and Experiments. *IEEE Transactions on Control Systems Technology*, 20(3), 652–662.

- Green, A. and Sasiadek, J. Z. (2004). Dynamics and Trajectory Tracking Control of a Two-Link Robot Manipulator. *Journal of Vibration and Control*, 1415–1440.
- Gripp, J. A. D. B., Santos, F. L., Bernardo, C. R., and Góes, L. C. S. (2012). Modeling and identification of a two-link flexible manipulator. *Symposium Series in Mechatronics, Section VII Robotics*, 5, 1092–1101.
- Guangzheng, P. G. P., Xuesong, W. X. W. and Yang, X. Y. X. (2002). Study on fuzzy PD control of planar two-link flexible manipulator. *2002 IEEE Region 10 Conference on Computers, Communications, Control and Power Engineering. TENCOM '02.*, 3, 1542–1545.
- Hariharan, M., Saraswathy, J. (2012). Infant cry classification to identify asphyxia using time-frequency analysis and radial basis neural networks. *Expert Systems with Applications*, 39(10), 9515–9523.
- Hariharan, M., Chee, L.S. and Yaacob, S. (2012). Analysis of infant cry through weighted linear prediction cepstral coefficients and probabilistic neural network. *Journal of Medical Systems*, 36(3), 1309–1315.
- Heidari, H. R., Korayem, M. H., Haghpanahi, M., and Feliu Batllet, V. (2011). A new nonlinear finite element model for the dynamic modeling of flexible link manipulators undergoing large deflections. *In International Conference on Mechatronics*.
- Huang, H. P., Jeng, J. C., Chiang, C. H., and Pan, W. (2003). A direct method for multi-loop PI/PID controller design. *Journal of Process Control*, 13, 769–786.
- Jaafar, H. I., Z. Mohamed, Amar Faiz Zainal Abidin, Z.A.G. (2012). PSO-Tuned PID Controller for a Nonlinear Gantry Crane System. *International Conference on Control System, Computing and Engineering*, 23–25.
- Jaafar, H. I., Mohamed, Z., Jamian, J. J., Kassim, A. M., Sulaima, M. F. (2014). Effects of Multiple Combination Weightage MOPSO for Motion Control Gantry Crane. *Journal of Theoretical and Applied Information Technology*, 63(3), 807–813.
- Jain, S., and Garg, M. (2013). Identification and Iterative Learning Control of Piezoelectric Actuator Based Nano-positioning System. *International Journal of Advance in Engineering Sciences*, 3(3), 88–93.
- Ji, X., and Familoni, B. (1994). Implementation of Self-Tuning Control of a Flexible Manipulator System. *In American Control Conference*, 2–3.

- Karthikeyan, P., Murugappan, M. and Yaacob, S., (2013). Multiple physiological signal-based human stress identification using non-linear classifiers. *Elektronika IR Elektrotechnika*, 19(7), 80–85.
- Khairudin, M. and Arifin, F. (2012). NN robust based-PID Control of a Two-Link Flexible Robot Manipulator. *International Journal on Advanced Science Engineering Information Technology*, 2(1).
- Khairudin, M., Mohamed, Z. and Husain, A. R. (2014). System Identification and LMI based robust PID control of a Two-Link flexible manipulator. *TELKOMNIKA*, 12(4), 829–838.
- Khairudin, M., Mohamed, Z., Husain, A. R., and Mamat, R. (2014). Dynamic characterisation of a two-link flexible manipulator: theory and experiments. *Advances in Robotics Research*, 1(1), 61–79.
- Kistler, (2015). Miniature PiezoBeam Accelerometer. Retrieved on 18 Sept, 2016 from [www.kistler.com](http://www.kistler.com).
- Lee, T. H., Ge, S. S. and Wang, Z. P. (2001). Adaptive robust controller design for multi-link flexible robots. *Mechatronics*, 11, 951–967.
- Leena, G., and Ray, G. (2012). A set of decentralized PID controllers for an n - link robot manipulator. *Sadhana-Academy Proceedings in Engineering Sciences*, 37, 405–423.
- Leitch, R. R. and Tokhi, M. O. (1987). Active Noise control systems. *IEEE Proceedings A Physical Science, Measurement and Instrumentation, Managements and Education*, 134, 525 – 546
- Lingbo, Z., Funchun, S., and Zengqi, S. (2006). Decoupling control of the Two-link flexible manipulator. *In Multiconference on Computational Engineering in Systems Applications*, 2045–2049.
- Loudini, M. (2013). Modelling and intelligent control of an elastic link robot manipulator. *International Journal of Advanced Robotic Systems*, 10(81), 1–18.
- Lu, H. and Liu, H. (2013). Ant colony fuzzy neural network controller for cruising vessel on river. *Applied Ocean Research*, 42, 43–54.
- Luyben, W. L. (1986). Simple Method for Tuning SISO Controllers in Multivariable Systems. *Industrial and Engineering Chemistry, Process Design and Development*, 25, 654–660.
- Benosman, M. and Le Vey., G. (2004). Control of Flexible manipulators: A survey. *Robotica*, 22(5), 533–545.

- Ma, X., Guo, S., Xiao, N., Guo, J., and Yoshida, S. (2012). NARX Model-based Identification for the Developed Novel Robotic Catheter Manipulating System. *In Proceedings of 2012 IEEE International Conference on Mechatronics and Automation*, 2225–2229.
- Mahamood, R. M. (2012). Direct Adaptive Hybrid PD-PID Controller for Two-Link Flexible Robotic Manipulator. *Proceedings of World Congress on Engineering and Computer Science*, 2.
- Mahamood, R. M., and Pedro, J. O. (2011a). Hybrid PD / PID Controller Design for Two-Link Flexible Manipulators. *In Proceedings of 2011 8th Asian Control Conference*, 1358–1363.
- Mahamood, R. M., and Pedro, J. O. (2011b). Hybrid PD-PID with Iterative Learning Control for Two-Link Flexible Manipulator. *Proceedings of World Congress on Engineering and Computer Science*, 2.
- Mansour, T., Konno, A. and Uchiyama, M. (2010). MPID Control Tuning for a Flexible Manipulator Using a Neural Network. *Journal of Robotics and Mechatronics*, 22(1), 82–90.
- Mansor, M.N, Yaacob, S.,Nagarajan, R., Hariharan, M. (2010). Detection of facial changes for ICU patients using KNN classifier. *2010 International Conference on Intelligent and Advanced Systems*, 298–301.
- Meira, A. S. (2015). Recursive nonlinear identification an electromechanical manipulator using the MIMO NARX model. *International Journal of Innovative Research in Advanced Engineering*, 2(1), 108–113.
- Mohammed, L. B., Hamdan, M. A., Abdelhafez, E. A. and Shaheen, W. (2013). Hourly Solar Radiation Prediction Based on Nonlinear Autoregressive Exogenous (NARX) Neural Network. *Journal of Mechanical and Industrial Engineering*, 7(1), 11–18.
- Morrisa, A. S., and Madani, A. (1996). Static and Dynamic Modeling of Two Flexible Link Robot Manipulator. *Robotica*, 14(3), 289–300.
- Murugesu Pandiyan, P. (2009). Vowels Classification Using MFCC and Feed Forward Neural Network. *Engineering Postgraduate Conference (EPC 2009)*, 60–63.
- Mute, D., Ghosh, S., and Subudhi, B. (2013). Iterative Learning Control of a Single-Link Flexible Manipulator Based on an Identified Adaptive NARX Model. *In Annual IEEE Indian Conference*.

- Napoli, R., and Piroddi, L. (2009). Nonlinear Active Noise Control Using NARX Model Structure Selection. *In 2009 American Control Conference*, 5616–5621.
- Nguyen, T., Vu, L., and Lee, M. (2010). Independent design of multi-loop PI / PID controllers for interacting multivariable processes. *Journal of Process Control*, 20, 922–933.
- Nguyen, V. B., and Morris, A. S. (2009). Using a genetic algorithm to fully optimise a fuzzy logic controller for a two-link-flexible robot arm. *Robotica*.
- Ogata, K. (2010). Modern control engineering. Fifth edition, Prentice-Hall Inc. Upper Saddle River, New Jersey.
- Pereira, E., Cela, J. J. L., and Feliu, V. (2007). A New Design Methodology for Passivity-Based Control of Single- Link Flexible Manipulators. *In IEEE/ASME international conference*, 1–6
- Pereira, E., Trapero, J. R., Díaz, I. M. and Feliu, V. (2009). Adaptive input shaping for manoeuvring flexible structures using an algebraic identification technique. *Control Engineering Practice*, 20, 138–147.
- Peza-Solís, J. F., Silva-Navarro, G., and Castro-Linares, R. (2010). Control of a Rigid-Flexible Two-link Robot using Passivity-based and Strain-feedback approaches. *In International Conference on Electrical Engineering, Computing Science and Automatic Control*, 476–481.
- Pham, H., and Anh, H. (2012). Adaptive Trajectory Modeling of Humanoid Robot 3-DOF Arm Using Inverse Neural MIMO NARX Model. *In International Conference on Control, Automation and Information Sciences*, 381–386.
- Physik Instrumente (PI) GmbH and Co. (2012a). P-876 DuraAct Patch Transducer. Karlsruhe, Germany.
- Physik Instrumente (PI) GmbH and Co. (2012b). E-835 DuraAct™ Piezo Driver Module Karlsruhe, Germany
- Pierezan, J., and Freire, R. Z. (2014). Improved Multi-Objective Particle Swarm Optimization for Designing PID Controllers Applied to Robotic Manipulator. *In 2014 IEEE Symposium on Computational Intelligence in Control and Automation (CICA)*, 1–8.
- Pitowarno, E., and Mailah, M. (2007). Robust Motion Control for Mobile Manipulator Using Resolved Acceleration and Proportional-Integral Active Force Control. *International Review of Mechanical Engineering*, 1(5), 549–558.

- Pradhan, S. K., and Subudhi, B. (2011). NARMAX modeling of a two-link flexible robot. *In Proceedings of Indian Conference (INDICON)*.
- Pradhan, S. K., and Subudhi, B. (2014). Nonlinear Adaptive Model Predictive Controller for a Flexible Manipulator: An Experimental Study. *IEEE Transaction on Control System Technology*, 22(5), 1754–1768.
- Rahimi, H. N. and Nazemizadeh, M. (2013). Dynamic analysis and intelligent control techniques for flexible manipulators: a review. *Advanced Robotics*, 28(2), 63–76.
- Rajalakshmi, M., Jeyadevi, and Karthik, C. (2014). Recurrent Neural Network Identification: Comparative Study on Nonlinear Process. *International Journal of Innovative Research in Science, Engineering and Technology*, 3(3).
- Reddy, M. P. P., and Jacob, J. (2014). Accurate Modeling and Nonlinear Finite Element Analysis of a Flexible-Link Manipulator. *International Journal of Mechanical, Aerospace, Industrial and Mechatronics Engineering*, 8(1).
- Rigatos, G. G. (2012). A Robust Nonlinear Control Approach for Flexible-Link Robots using Kalman Filtering. *Cybernetics and Physics*, 1(2), 134–143.
- Ruslan, F. A., Samad, A. M., Zain, Z., and Adnan, R. (2014). Flood Water Level Modeling and Prediction Using NARX Neural Network: Case Study at Kelang River. *In IEEE 10th International Colloquium on Signal Processing and Its Applications*, 7–9.
- Saad, M. S. (2014). Evolutionary optimization and real-time self-tuning active vibration control of a flexible beam system. *Ph.D. thesis*, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia.
- Sabzehmeidani, Y Hussein, M, Mailah, M, Zain, M Z, Abdullah, M R (2011). Intelligent Hybrid Control of Piezoelectric Actuated Micro Robot. *International Journal of Systems Applications, Engineering and Development*, 5(3),306–313.
- Sabzehmeidani, Y., Mailah, M. and Hussein, M., (2011). Modelling and control of a piezo actuated micro robot with active force control capability for in-pipe application. *International Journal of Modelling, Identification and Control*, 13(4), 301-309.
- Saha, S.; Das, S.; Pakhira, A.; Mukherjee, S.; Pan, I. (2012). Comparative Studies on Decentralizd Muliloop PID controller Design Using Evolutionary Algorithms. *In 2012 Students Conference on Engineering and Systems*.



- Sasaki, M., Asai, A., Shimizu, T., and Ito, S. (2009). Self-Tuning Control of a Two-Link Flexible Manipulator using Neural Networks. *In ICROS-SICE International Joint Conference*, 2468–2473.
- Sasiadek, J. Z. (2014). Space Robotics - Present and Past Challenges. *19th International Conference on Methods and Models in Automation and Robotics (MMAR)*, 926–929.
- Sawada, M., and Itamiya, K. (2013). A Position Control of 2 DOF Flexible Link Robot Arms Based on Computed Torque Method. *IEEJ Transactions on Electronics, Information and Systems*, 547-552.
- Selamat, N. A., Wahab, N. A., and Sahlan, S. (2013). Particle Swarm Optimization for Multivariable PID Controller Tuning. *In International Colloquium on Signal Processing and Its Applications*, 8–10.
- Shaharuddin, N. M. R., and Mat Darus, I. Z. (2012). Active Vibration Control of Marine Riser. *In Conference on Control, Systems and Industrial Informatics*, 114–119.
- Shawky, A., Zydek, D., Elhalwagy, Y. Z., and Ordys, A. (2013). Modeling and nonlinear control of a flexible-link manipulator. *Applied Mathematical Modelling*, 37, 9591–9602.
- Shin, H.-C., and Choi, S.-B. (2001). Position control of a two-link Flexible manipulator featuring piezoelectric actuators and sensors. *Mechatronics*, 11, 707–729.
- Shiu, S., and Hwang, S. (1998). Sequential Design Method for Multivariable Decoupling and Multiloop PID Controllers. *Industry and Engineering Chemistry Research*, 5885(97), 107–119.
- Shukla, A. and Karki, H. (2016). Application of robotics in onshore oil and gas industry — A review Part I. *Robotics and Autonomous Systems*, 75, 490–507.
- Subudhi, B., and Morris, A. S. (2002). Dynamic modelling, simulation and control of a manipulator with flexible links and joints. *Robotics and Autonomous Systems*, 41(4), 257–270.
- Sun, D., Mills, J. K., Shan, J. and Tso, S. K. (2004). A PZT actuator control of a Single Link Flexible Manipulator based in Linear Velocity Feedback and Actuator Placement. *Mechatronics*, 14(4), 381-401.

- Supriyono, H., and Tokhi, M. O. (2012). Parametric modelling approach using bacterial foraging algorithms for modelling of flexible manipulator systems. *Engineering Applications of Artificial Intelligence*.
- Supriyono, H., Tokhi, M. O. and Md Zain, B. A. (2010). Control of a single-link flexible manipulator using improved bacterial foraging algorithm. *In ICOS 2010 - 2010 IEEE Conference on Open Systems*, 68–73.
- Tan, K. K., Zhao, S., Chua, K. Y., Ho, W. K. and Tan, W. W. (2006). Iterative Learning Approach Toward Closed-Loop Automatic Tuning of PID Controllers, *Ind. Eng. Chem. Res.*, 45(12), 4093-4100.
- Tarique, A., and Gabbar, H. A. (2013). Particle Swarm Optimization (PSO) Based Turbine Control. *Intelligent Control and Automation*, 126–137.
- Tayebi, A., and Abdul, S. (2008). Robust Iterative Learning Control Design: Application to a Robot Manipulator. *IEEE/ASME Transaction on Mechatronics*, 13(5), 608–613.
- Tijani, I. B., Akmeliawati, R., Muthalif, A. G. A., and Legowo, A. (2011). Optimization of PID controller for flexible link system using a pareto-based multi-objective differential (PMODE) evolution. *In 2011 4th International Conference on Mechatronics*.
- Toha, S. F. and M.O.Tokhi. (2011). Multi-Objective PSO based Augmented Control of a Twin Rotor. *In 2011 International Conference on Mechatronics*.
- Tokhi, M. O., Mohamed, Z. and Azad, A. K. M. (1997). Finite difference and finite element approaches to dynamic modelling of a flexible manipulator. *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering*, 211(1), 145–156.
- Vakil, M., Fotouhi, R. and Nikiforuk, P. N. (2009). Manoeuvre control of the multilink flexible manipulators. *International Journal of Non-Linear Mechanics*, 44, 831–
- Vázquez, F., Morilla, F and Dormido, S. (1999). An Iterative Method for Tuning Decentralized PID Controllers. *In 14th IFAC World Congress*, 491–496.
- Vázquez, F. and Morilla, F. (2002). Tuning decentralized PID controllers for MIMO systems with decouplers. *In Proceedings of the 15th IFAC World Congress*.
- Vitiello, V., Lee, S., Cundy, T. P. and Yang, G. (2013). Minimally Invasive Surgery. *In IEEE Review in Biomedical Engineering*, 6, 111–126.

- Wang, Y., Chien, C., and Chuang, C. (2012). Adaptive iterative learning control of robotic systems using back-stepping design. *Transaction of Canadian Society for Mechanical Engineering*, 37(3), 591–601.
- Yang, T. (1991). Adaptive control of a single-link flexible manipulator with unknown load. *Control Theory and Applications*, 138(2), 153–159.
- Yatim, H., Mat Darus, I.Z. and Hadi, M.S. (2013). Particle Swarm Optimization for Identification of a Flexible Manipulator System. *In 2013 IEEE Symposium on Computers and Informatics*, 112–117.
- Yatim, H., and Mat Darus, I. Z. (2014). Self-tuning Active Vibration Controller using Particle Swarm Optimization for Flexible Manipulator System. *WSEAS Transactions on Systems and Control*, 9, 55–66.
- Yoshikawa, T., Ohta, A., and Kanaoka, K. (2001). State Estimation and Parameter Identification of Flexible Manipulators Based on Visual Sensor and Virtual Joint Model. *In International Conference on Robotics and Automation*, 2840–2845.
- Yurkovich, S., and Tzes, A. P. (1990). Experiments in Identification and Control of Flexible-Link Manipulators. *Control Systems Magazine, IEEE*, 10(2), 41–46.
- Zain, B.A., Tokhi, M.O. and Toha, S.F. (2009). PID-based control of a single-link flexible manipulator in vertical motion with genetic optimisation. *In 2009 3rd European Symposium on Computer Modelling and Simulation*, 355–360.
- Zebin, T., and Alam, M. S. (2010). Dynamic Modeling and Fuzzy Logic Control of a Two-link Flexible Manipulator using Genetic Optimization Techniques. *In Proceedings of 13th International Conference on Computer and Information Technology*, 418–423.
- Zhang, L., and Liu, S. (2014). Basis Function Based Adaptive Iterative Learning Control for Non-Minimum Phase Systems. *In World Congress on Intelligent Control and Automation*, 828–833.
- Zhang, X., Xu, W., Nair, S. S. and Chellaboina, V. S. (2005a). PDE modeling and control of a flexible two-link manipulator. *IEEE Transactions on Control Systems Technology*, 13(2), 301–311.
- Zhang, X., Xu, W., Nair, S. S. and Chellaboina, V. S. (2005b). PDE modeling and control of a flexible two-link manipulator. *IEEE Transactions on Control Systems Technology*, 13(2), 3796–3801.